A STUDY OF THE ERRORS
of the
BATHYTHERMOGRAPH

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Final Report

A STUDY OF THE ERRORS of the BATHYTHERMOGRAPH

by

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SECTION 1.0

ABSTRACT

This report has been written with the following purposes in mind:

1. To identify and tentatively define the errors in BT data.

2. To place on record a preliminary study to indicate to persons not familiar with the device the limitation of the bathythermograph as a scientific instrument.

The study of the errors of the bathythermograph is an investigation to determine the possible sources of error which may exist in the bathythermograph data. The investigation encompasses (1) intensive investigations of several anchor stations, i.e., data taken on a ship while in a fixed position, and (2) a comprehensive conference program with members of various Oceanographic Institutions to analyze their needs, methods, and processes.

In this report the errors are grouped together according to their error source, that is, instrument limitation, calibration technique, operational technique and data processing. These errors are classified wherever possible in accordance with standard mathematical nomenclature and practices. Correlation methods are also discussed, and proposed techniques for minimizing errors through correlation studies are suggested.

The result has led to a classification of possible sources of errors involved in obtaining bathythermograph information, and several techniques and suggestions for handling the bathythermograph data in order to recognize and minimize these errors. An extensive bibliography in Bathythermography and a glossary of terms are also included.

SECTION 2.0

INTRODUCTION

The Bathythermograph has provided the Navy and the Oceanographic Institutions with close to a half-million Bathythermograms. These Bathythermograms, taken over a period of ten years, indicating temperature versus depth structures in the oceans of the world, have been of immeasurable value in accumulating scientific data and thus furthering the general knowledge of oceanography.

The initial use of the Bathythermograph was in the qualitative studies of the temperature depth relationships. However, the advent of World War II created a definite application for the Bathythermograph as a military instrument. It was during this period that a large number of these data were continuously collected. Following the war, the Bathythermograph program was continued with the idea of collecting data which would be available for analysis at a later date.

Emphasis has gradually shifted from the qualitative contributions of the Bathythermograph to a more precise and more exacting quantitative requirement. Quantitative applications imply that a certain accuracy of measurement is expected from the BT. It is quite evident, therefore, that the extent to which the existing mass of data can be utilized depends largely upon the reliability of the information contained therein. This reliability is a function of many factors, such as the manufacture of the instrument itself, its calibration, state of maintenance, operation, and the methods of correcting, processing and correlating the data.

The National Scientific Laboratories for the past year have been concerned with a comprehensive study to determine the possible sources of errors which may exist in the Bathythermograph data. This study has included, (1) intensive investigations of several anchor stations, i.e., data taken on a ship while in a fixed position; and (2) a comprehensive conference program with members of various Oceanographic Institutions to analyze their needs, methods and processes. The result has led to a classification of possible sources of errors involved in obtaining Bathythermograph information and several techniques and suggestions for handling the Bathythermograph data in order to recognize and minimize these errors.

In this report these errors are classified wherever possible in accordance with standard mathematical nomenclature and practices. These errors are grouped together according to error source, i.e., instrument limitation, calibration technique, operation technique and data processing. Correlation methods are also discussed and proposed techniques for minimizing error through correlation studies are suggested.

The National Scientific Laboratories wishes to extend to the Oceanographic Fellowship its sincere gratitude for the generous and helpful assistance which many of its members so graciously extended to us.

SECTION 3.0

GENERAL DISCUSSION OF MATHEMATICAL ERRORS

In order to understand more completely the various classifications into which the Bathythermograph errors have been placed, it is advantageous to start with a general discussion of mathematical errors.

3.1. True Values and Probable Values

In determining an instantaneous temperature somewhere in the oceans one must assume that there is a true value which can be called an absolute value without error. However, the true value of most quantities can never be known because of the unavoidable errors in measurement and calculation, no matter how precise the instruments employed are.

In lieu of obtaining a true value one usually obtains the most probable value and along with the probable value a probable error. One can say that the probable value will not differ from the true value by more than the probable error.

3.2. Errors

The word "error" is a most common term used to describe a multitude of different conditions. One type of error has already been discussed, the probable error. In addition errors can be classified as determinate errors and indeterminate errors.

The term "true error" is often used, which mathematically defines the difference between a true absolute value and any single measured value. However, the true value is never known in the ocean, and therefore one needs to concern himself only with the probable error.

3.2.1. Determinate Error

Any error that is discovered and allowed for in magnitude and sign in the form of a correction for its effect is a determinate error. For example, comparison of an ordinary thermometer with a standard may reveal errors in the graduation of the former and result in a standard calibration. Every temperature measured with this thermometer would then be subject to an error of definite magnitude and sign which could be determined by reference to the standard calibration.

3.2.2. Indeterminate Errors

All errors that either cannot or are not properly allowed for in magnitude and sign are known as indeterminate errors. It is obvious that the correction for determinate errors will themselves be subject to errors and thus constitute one class of indeterminate errors.

3.2.2.1. Accidential Errors

A particularly important class of the indeterminate errors is that of accidental errors. Such errors are due to the combined effect of a large number of undetermined causes. Experience has shown that these deviations are inevitable in all measurements and that they result from small unavoidable errors of observations due to more or less fortuitous variations in the sensitivity of our measuring instruments and of our senses of perception.

3.2.2.2. Instrument Errors

In the instrument field one commonly encounters the "instrument error". This can be split into two parts: determinate errors and indeterminate errors.

Where the error is determinate, one sometimes refers to this as a "set". Where the error is indeterminate, it is referred to as instrument precision, or instrument reproducibility. The word precision denotes the extent to which a result is free from accidental errors. It is important to note that a result may be extremely precise and at the same time highly inaccurate, the precise result being in error by the magnitude of the determinate error.

3.2.2.3. Dependent and Independent Errors

Errors can furthermore be classified into dependent errors and independent errors. Where a quantity Y is a function of a quantity X, an error in X will produce a corresponding error in Y. This error in Y is known as the dependent error. Where the measurement of Y involves an accidental error which is not a function of X, it would be classed as an independent error. The total observed indeterminate error in X would be a function of dependent and independent errors observed.

Where the term "error" is used without classification or enlightenment, it is assumed that it means the indeterminate error, which in turn is a sum of the dependent and independent errors.

3.3. Accuracy

The accuracy of a value is a measure of how close to the true value or probable value the indicated measurement is likely to be. It in reality is the probable error, and takes into account both the determinate and indeterminate components of error.

3.4. Average Values and Average Errors

Average values and average errors are distinguished from probable values and probable errors by the fact that the former are arbitrarily defined by mathematics, and do not necessarily have any physical significance unless the assumptions which are made are valid.

3.4.1. Average Value

In considering a series of measurements of the same conditions, the average value or arithmetic average of the measurements is mathematically defined as the sum of the values of the individual measurements divided by the number of measurements taken. This is also sometimes called the "mean value". It should be noted that the average value is not necessarily the most probable value; it is simply the arithmetic average of the measurements which were taken.

3.4.2. Deviation

The net difference between any one reading of the series and the average value is called a deviation. Sometimes it is called a deviation. Sometimes it is called a deviation from the mean; sometimes it is called a variation; and it is sometimes loosely termed as "error". In its most mathematical sense it is called the residual. However, all these alternate terms should be avoided and it should simply be known as a deviation from the average or, more simply, deviation.

3.4.2.1. Average Deviation

The average deviation is defined mathematically as the sum of the absolute values of each individual deviation divided by the total number of deviations observed. The absolute value of course is the value without regard to its sign.

3.4.2.2. Standard Deviation

The standard deviation is mathematically defined as the square root of the "sum of the squares of each individual deviation divided by the number of deviations observed". The mathematical significance of the standard deviation can be found in most mathematical text books and will not be taken up here. It suffices to say that the standard deviation is considered the most probable average for the deviation where normal or Gaussian distribution of the readings is evident.

3.4.3. Discrepancy

Where it is desired to compare the simultaneous readings of two different instruments, as opposed to a series of measurements by a single instrument, the difference in reading between the two instruments can be called the discrepancy. This is an arbitrary term which will be used here to avoid ambiguity.

An average discrepancy will define the average of a group of discrepancies between two instruments measuring the same value. Its mathematical treatment is similar to the average deviation.

3.4.4. Variance

When it is desired to describe the change over a period of time of an average error or average deviation, it is convenient to call this change the variance.

3.4.5. Variability

In considering a series of measurements of conditions which do not change appreciably with time, it is possible that conditions will vary slightly in the immediate vicinity where the measurements are taken. The deviations in measurements will, therefore, be a function not only of the instrument variations, but also of variations in the conditions being examined. This latter variation is called variability and can be described in terms of average or standard deviations, where such deviations are a true measure of the change of conditions. The term variability should not be confused with the term variance used in the previous section.

3.5. Other Terminology

In an effort to clarify and perhaps to standardize the nomenclature used to describe the errors of the Bathythermograph a glossary of pertinent terms is attached as an Appendix to this report. It is hoped that this glossary will not only serve to clarify the terminology used in this report, but will also act as a basis for a more extensive and amended glossary in the field of Oceanography and Bathythermography.

3.6. Overall error as a function of individual errors

Where the overall error of an instrument is a result of the contribution of many individual types of errors as, for instance, reading error, correction errors, instrument precision and dependent error, the overall error cannot be less than the maximum of any one individual contribution, nor can it be greater than the

sum of all error contributions. The probability that the error will approach either this maximum or minimum is very remote. It is much more realistic therefore to establish a probable value based on each individual contribution.

The overall probable error is related to each individual contribution by the following equation:

$$\Delta E = \sqrt{(\Delta E_1)^2 + (\Delta E_2)^2 + \cdots + (\Delta E_N)^2} \tag{1}$$

This asumes that the individual errors and their magnitudes are subject to complete randomness and would tend to follow a normal distribution curve. Equation 1 does not take into account determinate errors since it is assumed that if an error can be established with regard to its magnitude and sign a proper correction can be made and such an error eliminated. However, in cases where the determinate is not accounted for, Equation 1 should be modified to read as follows:

$$\Delta E = \Delta E_{DET} \pm \Delta E_{INDET} \tag{1a}$$

The establishment of such a relationship between the individual contributions and the overall error can be found in any standard mathematical textbook and will not be derived here.

SECTION 4.0

APPLICATION OF ERROR TERMINOLOGY TO THE BATHYTHERMOGRAPH

The previous sections have described the mathematical definitions of errors and form the basis upon which the errors of the Bathythermograph can be analyzed and classified.

Consider first the true temperature value of any one point in the ocean at any one instant of time. Since temperature is an arbitrary reference level of thermal energy, it is subject to the errors of the reference instruments. However, a temperature can be defined within any accuracy desired, say for instance, $\pm$ 0.01°F.

Thus at time θ and depth D the temperature T can be assumed to have a definite value within the accuracy desired. At time θ plus $\Delta\theta$ and at the same depth D a second temperature T_2 can also be observed to the accuracy desired.

The question arises as to the exact relationship between T_1 and T_2. In a liquid medium such as the ocean the relationship between T_1 and T_2 can reflect the following four basic changes: (1) inaccuracies in the temperature sensing element (since temperature is a relative condition, the accuracy of the sensing element cannot be eliminated, even theoretically); (2) the change in the heat content of the mass of water, under measurement; (3) translation of the mass of water during the interval $\Delta\theta$, this change in mass reflecting a new temperature condition, or (4) where D is subject to accuracy of measurement, this change can reflect a change in the location of the instrument making the measurement during time $\Delta\theta$.

It is particularly important to note that any variations observed when a series of temperature measurements are made can be caused by any one of the four factors mentioned above. Thus when it is desired to study and make determinations concerning the change of the temperature in the ocean or the mass displacement occurring in the ocean, one must consider and recognize the variations which can arise from variations in the accuracy of the depth and temperature sensing elements. Conversely when concerned with establishing accuracy of the temperature and depth sensing elements one must be cognizant of the relative mass and temperature changes which are occurring in the ocean at the same time.

The actual changes in the temperature of the ocean and mass displacement during time theta (according to the above terminology) is ocean variability. The changes occurring as a result of the depth measuring element and the temperature sensing element, according to our mathematical definitions, are instrument errors, or more generally indeterminate errors.

Unfortunately, when dealing with a series of temperature measurements in the ocean, it is impossible to distinguish between the two types of changes; hence, ocean variability is always subject to the limitation of definition by the order of magnitude of the instrument errors. Conversely a study of instrument errors is limited by any ocean variabilities which may exist at the time the measurements are taken.

Probable values of the temperature of the ocean under various conditions can be established through series of measurements which take into account ocean variability and instrument erorrs. The accuracy of such a probable value is limited by the instrument accuracy and by the ocean variability which is occurring at that time.

4.1. Determinate Errors of the Bathythermograph

The location of the pen arm of the Bathythermograph with respect to the glass slide is an arbitrary one, since there are no marks on the glass slide which indicate actual values of the temperatures or depth. It is necessary to translate the tempera-

ture depth trace in a horizontal or vertical direction, or both, in order to have the temperature depth trace coincide with the actual values of depth and temperature of the ocean. This necessary translation is called depth set or temperature set. These depth and temperature sets and their corresponding correction factors (known as DCS and TCS) are, according to the terminology described above, determinate errors. These errors are determinate because they have definite magnitude and direction of sign and can be duly accounted for.

4.2. Indeterminate Errors of the Bathythermograph

The set of the Bathythermograph can change from time to time because of various factors which will be discussed later. This variation in set is then the indeterminate error contained in the determinate error.

In addition there are many other indeterminate errors to which the Bathythermograph is subject. (1) The Bathythermograph has an inherent reproducibility. (2) It may be subject to a hysteresis error. (3) It may have an error due to the rate of response of the instrument. (4) It may have an error due to operational conditions. (5) It may also have an error imposed upon it when corrections of the slides for the set are made. (6) When the slides are read they are subjected to reading errors. (7) Errors in temperatures may result from errors in depth. (8) Errors in initial calibration can produce calibration errors; and finally, (9) the error of the instrument can be a function of the depth, producing a variance in the error.

4.3. Bathythermograph deviations as a Function of Errors and Ocean Variability

It may be assumed, therefore, that in a series of temperature measurements in a fixed position in the ocean the average or standard deviation observed will be a function of the ocean variability and the errors involved in the instruments used to make the measurement. The relationship between the standard deviation and its various components again is given by Equation 1 which relates overall error and the contributions which make up the error.

$$\Delta E = \sqrt{(\Delta E_1)^2 + (\Delta E_2)^2 + \cdots + (\Delta E_N)^2} = \sqrt{\Sigma(\Delta E)^2} \qquad (1)$$

Concerning ourselves with standard deviations which are the correct deviations to employ where random error is involved, Equation 1 is rewritten as follows:

$$\sigma_{TOTAL} = \sqrt{\Sigma[\sigma]^2_{OCEAN} + \Sigma[\sigma]^2_{INSTRUMENT}} \qquad (2)$$

Where sigma equals standard deviation

Segregating the standard deviation into the standard deviation of temperature and standard deviation of depth, the following equation can be written:

$$(\sigma_T)_{TOTAL} = \sqrt{\Sigma(\sigma_T)^2_{OCEAN} + \Sigma(\sigma_T)^2_{INSTRUMENT}} \qquad (3)$$

The standard temperature deviations of the ocean and the instrument can be further broken down into their dependent and independent functions as follows:

$$(\sigma_T)_{OCEAN} = \sqrt{\Sigma(\sigma_T)^2_{INDEP} + \Sigma(\sigma_T)^2_{DEP}} \qquad (4)$$

$$(\sigma_T)_{INST} = \sqrt{\Sigma(\sigma_T)^2_{INDEP} + \Sigma(\sigma_T)^2_{DEP}} \qquad (5)$$

The dependent variability of the ocean is a function of the depth movement and the slope of the temperature depth trace at that point. Thus the influence of internal waves would produce a change in temperature at a given depth or a temperature variability which is actually a function of the water mass movement. (It should be noted that internal waves do not consist of random motion, and therefore (σ_T) DEP. will not represent a true average condition. Instead, an average based on harmonic wave motion should be employed.) Equation 5 also indicates a dependent error in the temperature sensing element due to the error in the depth sensing element. This error can be related to the depth error as follows:

$$(\sigma_T)_{DEP} = \frac{(\sigma_D)_{INDEP}}{S} \tag{6}$$

Combining (5) and (6):

Where S is the slope of the temperature-depth trace in ft/degree.

$$(\sigma_T)_{INSTR} = \sqrt{\Sigma(\sigma_T)^2_{INDEP} + \frac{1}{S^2}\Sigma(\sigma_D)^2_{INDEP}} \tag{7}$$

Similarly the standard deviation in depth is related to the temperature error and the independent error as follows:

$$(\sigma_D)_{INST} = \sqrt{\Sigma(\sigma_D)^2_{INDEP} + S^2\Sigma(\sigma_T)^2_{INDEP}} \tag{8}$$

The significance of the dependent error of temperature due to errors in depth can be best described as follows: Let us suppose we have an instrument capable of measuring to within .01°F and we wish to determine the temperature at a depth of 100 feet. Let us further suppose that at a depth of 100 feet the temperature varies from 70° at 95 feet to 60° at 105 feet, or 1° per foot. Let us further suppose that we are not able to locate the exact depth of the temperature sensing element to better than ± 5 feet.

While the temperature recorder may be accurate to within .01°F, the location will not be known except to within the nearest five feet; hence the element may have been anywhere from 95 to 105 feet. The temperature variation through this area is ten degrees; hence, the absolute value of the temperature at 100 feet cannot be determined with any greater accuracy than ± 5°. This relatively poor accuracy is a result of the dependent error in temperature due to the error in depth.

4.4. Measurements of Instrument Error by Special Tests

Since it is mathematically impossible to segregate the variability of the ocean and the instrument errors by observing a set of measurements, it is desirous whenever possible to determine instrument error independent of such measurements. This can often be done in special test such as will be discussed later. Whenever such errors can be independently determined they may be assumed to be contributing in accordance with Equation 1, and the independent value obtained may be subtracted from the equation to determine by difference the desired ocean variability components.

SECTION 5.0

ERRORS INHERENT IN THE INSTRUMENT

The Bathythermograph is an instrument primarily designed to measure change of temperature with change of depth. The word change is emphasized to point out the fact that the values of temperature and depth registered by the Bathythermograph are arbitrarily established by superimposed grids and correction factors.

5.1. Reproducibility

Given a Bathythermograph trace which represents a temperature versus depth structure, the ability of the instrument to reproduce that trace (in shape but not necessarily in the same coordinate location) is termed reproducibility. The rated reproducibility is usually assumed to be ± 0.1°F. and ± 2 feet in depth. The instrument's best demonstration of reproducibility is obtained by the superimposition of the up and down trace on a slide from a single cast where the variability of the ocean is low during the cast.

Reproducibility can also be described as instrument precision. The reproducibility or instrument precision is limited by the accidental errors which accumulate in the mechanics of the instrument and by the limitations and the accuracy of manufacture.

The reproducibility of the instrument is also limited by other sources of error which may creep into the picture, such as mechanical hysteresis, mechanical hesitations, and others. These will be discussed in separate sections. The value for reproducibility given above assumes that such other errors as may mar the reproducibility are not present. This statement is true in a carefully handled and calibrated instrument.

5.2. Accuracy of Registering Temperature Change with Change of Depth

While the reproducibility of an instrument may be good, the accuracy can well be poor. One will recall that accuracy is a measure of the instrument's ability to reproduce the actual or true conditions. For instance, should the change in the water be 10° and the instrument show a change of 15° repeatedly, the instrument would be highly reproducible but poor in accuracy.

Actually the accuracy of the Bathythermograph is governed by the assumptions which are applied when the grid by which these temperature changes are measured is made up. Remember that we are concerning ourselves only with temperature changes and not actual values. However, the grid must be employed to register temperature changes as well as actual values. The limitations on the accuracy which are imposed by the assumptions involved in making up the grid can best be demonstrated as follows: If it is assumed that an isothermal line is a straight line on the temperature depth slide and the Bathythermograph registers this line with a slight curve, the accuracy will be distorted by the amount of the curve. The accuracy could be made as good as the reproducibility if the grid is made with a slight curve. However, present techniques assume straight lines for isothermal conditions.

Likewise, in depth characteristics it is assumed that a movement of so many millimeters on the scale in shallow water will represent the same changes in deep water. Any failure of the instrument to meet this requirement will produce inaccurate change measurements. Discussions of the grid makeup will be deferred until the section on Calibration. It is well to point out here, however, that the in-

strument is normally considered to have the same accuracy in measuring changes of temperature with depth as quoted for reproducibility, that is ± 0.1°F or ± 2 feet in depth.

5.3. Hysteresis

The term hysteresis is borrowed from its more exact meaning (that is, a measure of the irreversibility of a closed work cycle) and is used here to describe the failure of the up and down trace to superimpose upon each other in an ocean condition of supposedly low variability. This failure to reproduce is manifested in these particular cases by a space between the two curves, either in their entirety or in any portion thereof, which is similar to the hysteresis curves obtained in irreversible work cycles.

Hysteresis can evolve from several sources listed as follows: (1) mechanical (2) response (3) ocean variability (4) change in lag conditions.

5.3.1. Mechanical Hysteresis

Should the pen arm be loose in its mount, it is quite possible that a play in the pen arm of several degrees could be present. This will produce up and down traces which are not superimposed but displaced with respect to each other by the amount of play in the pen arm. Under special ocean conditions, notably where there may be positive as well as negative gradients at different depths, the distortion as well as displacement can exist. Likewise, a loose glass slide or loose slide holder can produce mechanical hysteresis.

Such a hysteresis is an indeterminate error unless one of the traces is reproducible from slide to slide. One has then only to correct for the order of the magnitude of displacement between the up and down trace.

Slides have been noted where mechanical hysteresis of this nature has approached 3°F.

5.3.2. Response Hysteresis

The failure of the instrument to respond rapidly to sudden changes in temperature conditions (more accurately termed large temperature gradients) will produce hysteresis in that portion of the curve represented by displacement between the up and down trace.

This is most easily demonstrated by example. Consider a true state of conditions in the ocean represented by a step-wise Bathythermograph; that is, an isothermal section followed by a horizontal section representing say a drop of 10° followed by another isothermal section. Hysteresis will result because of the failure of the instrument to follow this rapid gradient change. The down trace will be below the horizontal portion of this step while the uptrace will be above the horizontal portion of the step.

The response characteristics of the machine is rated such that the 63% of the temperature range can be traversed in the period of 0.27 seconds. This rate of response should be adequate for almost all conditions which would be encountered in the ocean. However, one must remember that the ability of the instrument to follow the changes in gradient of the ocean is a function of the rate of lowering and raising the instrument. This possible source of error is discussed in a later section under Operation.

Rate response curves can be calculated according to the following set of equations:

Let T = indicated temperature recorded by the bathythermograph at any time θ.

Let T_o = initial temperature of bathythermograph.

Let T_a = actual temperature of surroundings of bathythermograph.

Let τ = a constant.

Then:

$$\frac{dT}{d\theta} = \frac{1}{\tau}(T_a - T) \tag{1}$$

For T_a = constant, the solution to (1) is as follows:

$$\frac{T - T_a}{T_0 - T_a} = e^{-\frac{\theta}{\tau}} \tag{2}$$

Tau may be experimentally determined as follows: Assume the BT is moved suddenly from T_o to T_a (which is experimentally done by plunging the BT suddenly into a cold bath for instance).

The relative response conditions at time $\theta = \tau$, would be as follows:

$$\frac{T - T_a}{T_0 - T_a} = e^{-1} \tag{2a}$$

Rearranging:

$$\frac{T_0 - T_1}{T_0 - T_a} = 1 - \frac{1}{e} \cong 0.632 \tag{2b}$$

Where T_1 = indicated temperature at time $\theta = \tau$

Since $T_o - T_a$ is the total change that the BT would undergo, and $T_o - T_1$ is the change actually gone through at time $\theta = \tau$, one has only to register the time at which the BT records a temperature approximately 63% of the way between the initial temperature and the bath temperature. Time value is numerically equivalent to τ, the response constant of the BT.

Normally the response time is reported for such instruments, and represents the time to travel 63% of the desired scale limits.

There have been many questions which have arisen with regard to the response characteristics of the instrument. These questions all point to a definite need for more experimental programs to be undertaken with regard to rate response. Rate response knowledge is important in order to differentiate between this type of hysteresis and the hysteresis resulting from ocean variabilities.

5.3.3. Hysteresis Due to Ocean Variability

The up and down traces may not coincide in portions of the BT trace because of a change in the ocean conditions between the time the downtrace was made and the uptrace was made. This notably occurs in the presence of internal waves. This is not an error of the instrument, but is a true measure of ocean variability. However, as previously pointed out, ocean variability cannot be distinguished from instrument error in any one given set of data except by independent means of checking.

5.3.4. Change in Lag Conditions

In some rare cases hysteresis can result from a change in lag conditions. This is brought about for example by allowing the Bathythermograph to plow into the mud. When the Bathythermograph comes up again it is covered with mud, thus insulating the thermal element. The response to temperature changes is thereby delayed and a curve displacement results. Such a displacement may result also from sudden shock which will change the location of the pen arm. This type of displacement is usually a permanent one, however.

5.4. Response Characteristics

5.4.1. Response Hysteresis

Response hysteresis has already been discussed in the above sections.

5.4.2. Response at Initial Depth

There is good cause to believe that the Bathythermograph may not respond with respect to its pressure sensitive element in the initial depths.This is borne out by experiments which compare the Bathythermograph trace to traces made by thermister beads.

The lack of this response of the pressure bellows in the initial depths followed by a sudden response of this element to the conditions would result in a straight or isothermal line from zero feet to the point at which the bellows element responded. The temperature registered for the zero depth value therefore would be that actually found at the depth at which the Bathythermograph responded, say 10 feet. This is vitally important when considering the desirability of checking the absolute value of the zero depth reading of the instrument with an independent measurement such as the bucket temperature. If the Bathythermograph is not registering an actual zero depth value but rather a line representing the 10 foot value, such comparisons can be in great error. This is further discussed under temperature correction applications.

5.4.3. Mechanical Hesitation

In just the same manner as the Bathythermograph is believed to hesitate in the initial depths before responding, so it is quite possible for the Bathythermograph to hesitate all along its path producing a series of minor wiggles in the Bathythermograph trace. These minor wiggles, if they are due to mechanical hesitation, are consequently a source of error.

There are no experimental data to support the presence and, if so, the magnitude of these mechanical hesitations. It can only be stated at this point therefore that such mechanical hesitations can exist as a possible source of error and should be considered whenever wiggles in a trace become an important factor in analysis of the data.

These mechanical hesitations could easily look like true ocean variability, or thermal microstructure. Some data suggest that the Bathythermograph does not reproduce thermal microstructure while other data indicates very fine wiggles equivalent to thermal microstructure. This indicates that a resolution of these errors be made by further research.

5.5. Bathythermograph Sets

All of the conditions discussed above are representative of possible sources of errors which will reflect in the reproducibility and accuracy of the instrument in its

ability to measure temperature change with change in depth. So far nothing has been mentioned about the recorded values as related to the actual temperature values of the ocean.

The process of establishing reference values for the Bathythermograph trace is simply one of transposing the slide containing the grid calibrations until the mark which was made by the Bathythermograph pen arm at the zero depth level corresponds to the zero depth level on the grid and the temperature value corresponds to the actual temperature of the ocean, possibly recorded by a separate instrument.

When the instrument is released by the manufacturer, or after it has been checked, the positioning of the grid is made at that time so that the Bathythermograph slides supposedly read not only the changes, but also the actual values represented there.

Any departure of the trace thereafter with respect to its absolute position relative to the grid will produce a false reading. This false reading will be in error by a determinate amount, i.e., the magnitude and direction of the error can be established. These determinate errors which manifest themselves in terms of displacement of the trace from the actual point at which it should be located are called depth and temperature sets.

It should be well noted that the Bathythermograph was not designed to correct or maintain its position relative to the grid, but only to reproduce changes. The position relative to the grid is a man-made one and is an arbitrary one. This attempt to position the grid to read actual values and the correction techniques involved is a source of indeterminate errors. These errors will be taken up in a later section.

5.6. Instrument Failures

5.6.1. General

The greatest source of errors occur naturally when the instrument components fail or become damaged. The most common sources of failure are listed below.

5.6.2. Bending of Pen Arm

The pen arm position relative to the grid is established at the point of calibration or manufacture. Should the pen arm be bent the result would be a displacement of the trace and the resultant error in the set. This condition has been quite prevalent as a result of two things — (1) if the Bathythermograph is left in the sun the heating element carries the pen arm beyond its normal limits and thus bends it, and (2) if the Bathythermograph is retrieved from the water too fast, the pressure element overrides and jams against the pen arm, thus bending it, in some cases.

Corrective measures for both of these conditions have been suggested in the literature. It merely suffices here to repeat that such corrective measures should be employed so as to minimize these possible sources of error.

5.6.3. Superimposition of Trace and Destruction of Trace

At present the up and down trace are intended to superimpose on each other. While this indicates the reproducibility of the instrument, it is often time disadvantageous, whenever it is desirable to make accurate calculations with regard to temperature structure. It is often impossible to determine which is the up and which is the down trace and thus to follow it through continuously. It would be decidedly advantageous to design for scientific use an instrument which displaces the uptrace

from the downtrace by a standard amount, say 5°, thus producing two independent traces which can be distinguished at all times, and which nevertheless still can be superimposed for comparsion by any number of simple techniques.

A further disadvantage of the superimposition is that often times the entire top portion of the trace is destroyed by the pen arm after the Bathythermograph has surfaced and skips along the waves. The jarring and jolting of the pen arm causes the destruction. A pen lifting attachment which removes the pen from the trace in the last 50 feet of travel has been described previously in the literature. This is an advisable procedure in that it will preserve the downtrace of the pattern.

5.6.4. Bellows Failure

The 900 foot Bathythermographs have been demonstrating a high percentage of bellows failures through fatigue. Failures have been occurring after one hundred to two hundred lowerings; there is even skepticism as to the accuracy of the depth sensing elements even before complete failure. One example was cited where a cruise which was carrying eight 900 foot Bathythermographs failed to bring back one operable instrument, all having failed because of bellows fatigue. The remedy seems to be in the type of bellows used and the mechanism for strengthening and guiding the bellows. Corrective measures are being taken by the Bureau of Ships.

5.6.5. Loose Parts

A great many Bathythermograph traces are rendered invalid because of loose parts such as the pen arm, producing hysteresis and distortion. The best remedy for this is more frequent checking of the Bathythermographs during operation by qualified personnel.

SECTION 6.0

ERRORS INTRODUCED BY CALIBRATION AND RECALIBRATION OF THE BATHYTHERMOGRAPH

6.1. General

The calibration tests to date are the only tests that a Bathythermograph receives which can in any way check its accuracy and reliability. These calibration tests are in general too infrequent and not of sufficient extent. Calibration tests under idealized conditions and employing secondary temperature and depth measuring instruments can provide some reliable indications of the possible sources of errors of the Bathythermograph, these being determined experimentally independent of ocean variability.

At the same time it should be noted that calibration techniques are also a possible source for the introduction of errors. These errors would originate primarily from failure to determine whether or not the Bathythermograph has linear characteristics. In particular there is evidence to show that the pressure elements are not linear with respect to depth measurements. These conditions can be determined experimentally in the calibration procedures, however.

The present techniques for calibration and recalibration procedures are satisfactory as far as they go, but do not cover sufficient grounds. Briefly the problems may may be summarized as follows:

a. No tests are run before Bathythermograph is repaired.

b. Tests are not conducted often enough on each Bathythermograph unit.

c. Test log and history of repair of Bathythermograph are not kept at all or is incomplete.

d. There is no uniformity between test stations.

e. The capacity of the testing stations is too small for the amount of Bathythermographs which must be calibrated.

f. The tests are not complete enough.

  (1) Do not account for hysteresis.

  (2) No rate of response tests.

  (3) No stability tests (run through a second time to see if same as first time) (initial fatigue of new parts).

  (4) No smoothness tests are run (change of temperature with change of depth under idealized conditions to test smoothness of response).

6.1.1. Pre-Repair Tests

There are at present no tests conducted (except in certain special cases) to determine how much in error an instrument is before the instrument is cleaned, repaired, and put into shape. Such a pre-repair test would give valuable information which would aid in evaluating the reliability of the data taken by the instrument, and the corrective factors to be applied when indicated, particularly if a BT log was kept.

It is true that at present the majority of instruments sent in for recalibration are completely inoperative to begin with. This condition lies partly with the length of time an instrument is in use before it is sent back for recalibration.

It is also true that many instruments may be cleaned up and repaired to a minor degree by the field personnel before being returned to the testing stations, thus rendering pre-repair tests ineffectual. But these conditions can be ironed out.

6.1.2. Frequency of Calibration

As mentioned above, most instruments are recalibrated when they are completely inoperative. There should be a properly scheduled system of recalibration of instruments without their having to become inoperative. Recalibration at frequent periods serves to produce more reliable data and more reliable corrective factors for data taken. A three months recalibration period has been generally suggested as a goal to shoot at. Of course, the more frequent, the better, commensurate with reasonable cost, etc.

6.1.3. Bathythermograph Test Log and Repair History

In many cases a history of repair is kept of a given Bathythermograph. This has been confined to special instruments used by scientific personnel.

A complete, up-to-date, test log and repair history for a bathythermograph unit would (1) aid immensely in the evaluation of the data obtained, (2) produce a statistical record of Bathythermograph performance, showing its main manufacturing weaknesses, and the major causes for damage by the personnel operating them, and (3) establish the optimum time for scheduled recalibration before becoming inoperative.

6.1.4. Uniformity Between Testing Stations

Standardization of testing procedures requires that the various testing stations employ the same techniques for testing, and if at all possible, the same type of testing equipment. In addition, the independent absolute measuring devices should be cross calibrated between stations to insure standard absolute values.

At present there is some standardization of testing stations attempted through the proper Navy manuals for testing procedures, but in general the actual practices followed are quite varied. It seems quite in order that uniformity between stations be a part of a general program outlining standardization for all test procedures.

6.1.5. Capacity of Testing Stations

The older installations hold one or two Bathythermographs for simultaneous test cycles. The newer units on the West Coast can hold up to six units. In view of the large number of Bathythermographs that need frequent recalibration, the testing stations should be designed with the idea of being able to test several units at one time. This is particularly important if the testing cycle is increased in scope to account for the aforementioned features.

6.1.6. Hysteresis

It is important that a test pattern to inspect for hysteresis be made in the calibration procedure. A concurrently acting temperature versus depth trace which was then reversed would show any tendency to hysteresis in the instrument.

6.1.7. Rate of Response

No test at present computes the rate of response of the Bathythermograph to changes in temperature and depth. Rate of response is particularly important in

waters of high thermal gradients. Certain recent anchor stations indicate a need to investigate the rate of response further. Incorporation of rate of response into the testing procedures seems advisable as part of the procedure of checking all phases of operation of the Bathythermograph.

6.1.8. Reproducibility Tests

The simple procedure of running a Bathythermograph through two simultaneous cycles would give adequate determination of the ability of the Bathythermograph to reproduce results, and an indication of its stability. It is a fairly well established fact that when a Bathythermograph is repaired, especially when a bellows is replaced, the first flexing under water pressure it receives produces an initial fatigue set. It is almost mandatory that a new or freshly repaired instrument be flexed to overcome this initial fatigue set.

6.1.9. Smoothness Tests

Major and minor wiggles have long been observed in the traces of operated Bathythermographs. There is much debate as to whether these wiggles are present in the ocean or the instrument.

The same tests that would be conducted for hysteresis would also show the smoothness of response, and would resolve the origin of the wiggles as to instrument or ocean. Operationally, the smoothness test would show if the instrument had any inclination to hang or catch along its temperature depth route. This is especially important in the very top layers, where small amounts of friction and inertia will prevent the instrument from responding.

6.1.10. Standardization of Testing Procedure

It appears well in order that the whole picture of calibration be thoroughly studied with a view to recommending the best and most desired testing procedures. Adoption of such recommendations would serve to standardize the entire testing program, giving more uniform and more reliable results.

SECTION 7.0

ERRORS INTRODUCED BY OPERATING TECHNIQUES

Errors introduced by the operating technique take into consideration two distinct features: (1) Errors produced by the technique itself, and (2) Errors produced by the personnel operating the Bathythermograph.

7.1. Errors Produced by Handling the Bathythermograph

The major faults of the Bathythermograph from an operational standpoint may be summarized as follows:

a. Can be operated with slide not in all the way.

b. Can be broken by leaving in the sun.

c. Can destroy the trace in the surface layer when recovered from the cast.

While it would be considered advantageous if the instrument could be designed not to operate unless proper seating was first accomplished, it is still the fault of the personnel not to seat the slide properly.

Again a fault of the personnel, the instrument's pen arm can be seriously bent if left in the sun exposed to too high a temperature. Some manner of disengaging the pen arm would eliminate this very common error.

Destruction of the upper part of the trace is often caused by the skipping and bouncing of the instrument upon recovery. This has been eliminated in newer instruments by a pen lifting device which disengages the pen on the "up" trace of the cast in the last fifty feet approaching the surface. Sometimes, however, this disengaging device, actuated by the protecting sleeve, renders the Bathythermograph inoperative unless care is taken to have the sleeve in the proper position, this proper position being left to the attention of the operating personnel. The result has been blank slides.

7.2. Errors Produced by Supplementary Equipment

The principal supplementary equipment is the winch used to raise and lower the Bathythermograph. One of the major operational difficulties is bringing the Bathythermograph aboard, especially in rough weather. A one speed winch causes the Bathythermograph to swing violently in an arc as it frees the water, and sometimes results in jamming the Bathythermograph against the davit blocks. An adjustable speed winch would facilitate handling and boarding of the Bathythermograph.

As previously pointed out, there is evidence to support the fact that the speed of raising and lowering the Bathythermograph can effect the trace. A number of Bathythermographs lowered experimentally by hand showed no hysteresis whereas other Bathythermographs lowered under the same conditions, but on the winch, showed considerable response hysteresis. It is quite possible that the speed of raising and lowering the Bathythermograph can introduce a source of error under certain conditions.

In view of the high degree of damage the Bathythermographs suffer, it seems advisable to study a little more thoroughly the design and operation of the winch and davit system used to lower and raise the Bathythermograph. Extra expense in improving the supplementary equipment might be more than compensated for by the savings in the Bathythermographs and improvement in the Bathythermograph data.

7.3. Errors Produced by the Operating Personnel

The chief comment which can be made concerning the operation of the Bathythermograph is that the ultimate accuracy of the data taken by the instrument depends as much upon the reliability of the personnel as it does upon the instrument itself. It has been stated that portions of the data received from the tactical personnel cannot be regarded as reliable.

Most of the personnel professionally engaged in oceanographic work appreciate and understand the limitations of the Bathythermograph instrument, i.e., its inability to picture microstructure, its peculiarities with respect to hysteresis, its dependent errors of temperature and depth, and its variations from the absolute measurement of temperature and depth. These limitations are not generally understood, however, by the majority of Navy personnel who operate the Bathythermograph; nor is the care and use of the instrument understood and appreciated by those engaged in gathering a great percentage of the Bathythermograph data.

It is strongly recommended that an abstract be prepared on the capabilities, limitations, peculiarities, and characteristics of the Bathythermograph and directed in its preparation towards the data procurement personnel. It is felt that if all levels fully understand the importance of the data and the proper treatment of the instrument in the collection of this data, more of the data collected would be reliable.

The errors manifest themselves in terms of (1) the lack of care and handling of the instrument causing jarring and failure, (2) lack of maintaining proper and complete records to the extent of falsifying or not taking readings, and (3) errors involved in reading instruments and reading the Bathythermograph slides.

A considerable amount of data could be interpreted and analyzed if the operating personnel were careful in maintaining complete notes on conditions that existed at the time of the Bathythermograph cast. For instance, such things as double traces, sudden changes in sets, abnormal BT traces, blotches, etc., if accompanied by the operating experience at that time would provide invaluable information. This will require the taking personnel to examine each BT card when it is taken to determine if such irregularities existed, and to report any abnormal conditions which may have existed simultaneously. Failure to do this results in lack of reliability of the data taken.

SECTION 8.0

ERRORS INTRODUCED BY PROCESSING OF THE BT DATA

The method of processing BT data primarily involves superimposing the calibrated grid of the Bathythermograph over the raw slide and thereby establishing their relative positions, giving not only the correct temperature changes but also the correct temperature values.

Assigning correct temperature values involves locating the grid with relation to the slide through the medium of temperature and depth set corrections. In the field and under the assumption that no changes have occurred since calibration, the grid can be matched to the raw slide by matching the edges of the grid with the edges of the slide. Whenever a set develops in the Bathythermograph, the grid is then moved from its original coincident position by the set correction to account for this error.

It is necessary to establish correct temperature values for each Bathythermograph in cases where it is desired to compare a series of Bathythermograms taken over a period of time. In this case one is not only interested in the relative changes which occur on any one Bathythermogram, but also the relative changes which occur between Bathythermograms. These relative changes which occur between Bathythermograms must not include the changes in the temperature and depth correction factors of the Bathythermograph.

The change in sets of the Bathythermograph is a greater source of error than any variance in its precision or reproducibility. Since sets are determinate errors, the magnitude and direction can be calculated and allowed for. It is this process of establishing the determinate error and making proper corrections which warrants careful analysis.

8.1. Temperature Correction Technique

The present practice employed is to correct Bathythermograph temperatures by a supplemental independent surface temperature measurement. This is accomplished by making simultaneous bucket temperature casts or by reading the water injection thermometer.

The technique for applying the temperature corrections varies considerably, the technique being dependent primarily upon the reliability of the independent surface temperatures taken. These in turn depend upon the experience of the personnel and the care they exercise in taking the surface temperature measurements.

Where exceptional care is taken in obtaining bucket temperatures, individual corrections are applied to each Bathythermogram. This technique is limited to special scientific studies where the precision desired is justified by the experience of the personnel taking the data.

The majority of corrections are not applied individually to each corresponding Bathythermogram. Instead, the discrepancy between each surface temperature and the corresponding Bathythermogram are accumulated for one specific Bathythermograph over a period of time and averaged. This average discrepancy is used as a correction factor, and is applied to each Bathythermogram involved in the averages when corrected photographic prints are made.

The reason for taking averages is twofold: first, it facilitates the photographic process when only a single correction setting has to be made. Secondly, the independent surface temperature measurements are themselves subject to considerable inaccuracies. These inaccuracies are ironed out, or so it is believed, when a series of measurements are averaged.

The length of time over which these averages are taken varies considerably. These periods end whenever there seems to be some sharp break in the discrepancies (difference between surface value of the Bathythermograph and the independent surface measurements) noted for a particular instrument.

Sometimes no correction factor is applied. This occurs when considerable doubt is cast upon the validity of the independent surface thermometer readings (bucket temperature or injection temperatures). One check for inconsistencies is accomplished by comparison with a chart which shows average surface temperatures for various times of the year for various ocean areas. Another check is gotten by looking for unwarranted variations in the reported surface temperature values while the Bathythermogram shows a steady repetition.

8.2. Depth Correction Technique

Each Bathythermogram is subject to errors along its depth scale which are noted by comparing the zero depth grid line to the horizontal trace usually found on all Bathythermograph slides at the true zero depth level, caused by the rapid change in temperature from air to water.

Individual corrections are seldom, if ever, applied. Again an average discrepancy is recorded for a series of Bathythermograms, and an accumulated average of varying periods taken. Interruptions of these averages are effected whenever a sharp change in the values is noted. A single setting facilitates the photographic process, as was the case in temperature corrections.

8.3. Errors Involved in Correction Techniques

The methods described above to establish temperature and depth correction factors involve four basic weaknesses which are possible sources of error. These are summarized as follows:

1. Correction of Bathythermograph to poor secondary information.
2. No allowance for variations in set unless there is a sharp discontinuity.
3. Lack of reliability of the zero depth value of the Bathythermograph.
4. Applying the corrections at the most unstable point of the ocean, the surface.

8.3.1. Poor Secondary Information

The ability to correct the Bathythermograph to read correct temperatures is limited by the extent to which the independent measurements are reliable. Here is where the human element plays a very important part. The independent temperature measurements, whether they are made by a bucket thermometer or injection thermometer, must be correctly read and correctly recorded. As has been previously pointed out under Section 7.3, the operating personnel often record erroneous data either accidentally or otherwise. This is especially true where injection thermometers are employed for the independent measurement. The thermometers are not read correctly and in many cases are not read at all, but the last reading is merely repeatedly recorded.

Another major contribution to incorrect data is the unreliability of the independent measuring instruments themselves. Injection thermometers notably cannot be read any better than ± 0.5°F and yet are expected to correct the Bathythermograph to within 0.1°F. More often than not the injection thermometers are stuck, or are off calibration. There is at present no program requiring these injection thermometers to be calibrated. A small expenditure to provide a much more accurate injection thermometer would increase the reliability of tremendous quantities of Bathythermograph data which are taken at great cost.

Similarly the bucket thermometer which is normally provided in the kit in which the Bathythermograph comes is entirely inadequate in its readability. Here again a better thermometer should be provided, one which has a readability to the accuracy desired of ± 0.1°F.

Another source of error is a poorly designed bucket with which surface samples are taken. There are considerable data to show that the temperature can drop several degrees between the time the sample is taken and the time it is read, due to high evaporation losses. In other cases the temperature can rise from the radiation of the sun causing heating of the bucket. There are buckets which have been designed to provide for good insulation and low evaporation losses, so that the temperature of the water when read will be the same as the temperature when the water was actually sampled.

If in any case the water sampled for independent measurement is not the same as the water through which the Bathythermograph was lowered, the independent measurement will bear no accurate relationship to the Bathythermograph itself. This is more completely discussed in Section 8.3.4.

8.3.2. Variation in Sets

The correction of the Bathythermograph involves an independent measurement of the water by another instrument. It is assumed that these measurements are made simultaneously. The difference between the reading of two instruments taking simultaneous measurements has been termed discrepancy. This discrepancy is a determinate condition with an indeterminate portion represented by the contribution of the errors of the two measuring instruments.

The variance in a discrepancy can be theoretically caused by three different conditions. (1) The Bathythermograph can contribute 100% of the variation due to its variation in set. (2) The independent measuring instrument can contribute 100% of the variation, due either to its inaccuracy or to the fact that it is not really measuring a simultaneous condition. (3) The variation and discrepancy can be caused by the combined contribution of both instruments, as pointed out in (1) and (2).

Where condition (1) is in evidence, then the application of an average discrepancy as described in Section 8.1 above does not allow for the variation in set of the Bathythermograph, therefore, it does not correct the Bathythermograph to the extent to which it could be corrected if each individual discrepancy were applied to each Bathythermograph.

If condition (2) exists, then the varations in the secondary measuring instrument can be smoothed out by employing average discrepancies such as described in section 8.1. Where the secondary measurements are considered to be less accurate than the Bathythermograph itself, consideration can even be given to applying no correcting factor at all. Where condition (3) exists, it must be determined whether these conditions lie closer to condition (1) or condition (2) and thence where the individual or average correction should be applied.

Actually all three of these conditions can and do exist. Where exceptionally careful personnel are employed and exceptionally good secondary measuring instruments are used, individual correction should be applied, since this corresponds to condition (1). Where Bathythermographs have been taken using injection thermometers for corrections, it has been shown that these correspond more closely to condition (2) and average corrections are in order or even no corrections at all. All Bathythermograph data should be studied to determine whether they correspond to condition (3), and if so which would be the better method to employ, individual correction or average corrections. Failure to use the best method for correcting the data can inject greater sources of error than not employing any correction to the Bathythermograph slide.

8.3.3. Factors Affecting Zero Depth Reading of the Bathythermograph

It has been pointed out previously that the zero depth value of the Bathythermograph may in actuality not be a zero depth value at all but is the value at whatever depth the pressure element of the Bathythermograph responded. Should, for instance, the Bathythermograph pressure element stick until the depth of five feet is reached before it suddenly moves, the line it forms from 0 to 5 feet will register the temperature at five feet. Furthermore, it is at the surface where considerably high gradients as well as thermal microstructure exist. Failure of the Bathythermograph to respond either in temperature or pressure in the initial depth of even one foot will produce erroneous results when attempting to apply correction factor at that point.

8.3.4. Reliability of Surface Bucket Samples

Not only does the extreme temperature gradient in the few inches of the surface have an effect upon the actual value recorded by the Bathythermograph, it also has a considerable effect upon the reliability of the sample which is taken by the bucket. Thermal gradients exist not only vertically, but also horizontally. The surface bucket scoops up a sample of the first few inches of the surface of the water. The temperature that this represents is being compared to the zero depth reading of the Bathythermograph which is in reality some average of the first few feet due to the inherent lag of the instrument in the initial descent. Should there be any time lag between the taking of the bucket sample and the lowering of the Bathythermograph, it is quite possible that the bucket will scoop up a sample which is separated from the point at which the Bathythermograph was lowered by an extreme horizontal gradient. In other words, the bucket sample is a poor representation of the surface conditions of the ocean since it samples such a small amount of the surface, and this amount is subject to random surface variations which will not be reflected in the Bathythermograph record. This is particularly true on the edges of currents.

Where injection temperatures are read, the injection intake is considerably below the surface of the water. Thus the injection temperature does not represent a surface reading, but a reading in the subsurface, the distance below the surface being a function of the pitch and roll of the ship. The injection thermometer cannot be regarded, therefore, as a reliable indication of the surface conditions at the point where the Bathythermograph was lowered.

The attempt to compare Bathythermograph surface value with an independent surface temperature measurement is, in theory at least, a poor technique because of the fact the sampling is being done in the most unstable portion of the ocean. Comparisons would be much better made at some considerable depth where the ocean is more stable and where conditions do not vary so radically in their spacial relation-

ships. While this in practice may be hard to achieve, nevertheless definite consideration should be given to establishing comparison at some other point, rather than the surface of the ocean.

Another approach to the problem would be to establish whether the Bathythermograph reads an average value of the first few feet or an actual value. If the former is true, then some means should be made for obtaining an average bucket sample rather than a superficial surface sample. Improving the sampling conditions might well be the answer to increased accuracy in establishing Bathythermograph corrections.

SECTION 9.0

PROPOSED METHODS FOR DISCOVERING, EVALUATING, AND MINIMIZING ERRORS IN EXISTING AND FUTURE BATHYTHERMOGRAPH DATA

The recognition and classification of the various sources of error which are involved in the collection and processing of Bathythermograph data provides definite indications as to methods of attack for evaluating and minimizing these errors when employing these data for theoretical studies.

These techniques for minimizing errors must bear a direct relationship to the use to which the Bathythermograph data is to be put. For instance, should the study only require a knowledge of temperature differences between one depth and another, it is not necessary to be concerned with the absolute values which the Bathythermograms represent. On the other hand, should the studies be concerned with the variability of the ocean with respect to time, then all variations in correction factors must be eliminated, or at least minimized as best one can.

Minimization of the error in reproducibility in the Bathythermograph lies for the most part in experimental investigations. Such investigations will not be taken up here, but suggestions will be found in Section 10.0, Recommendations. On the other hand, minimization of errors in Bathythermograph sets lend themselves to mathematical studies. These are taken up in detail below.

9.1. Establishing the Reliability of the Surface Temperature Correction Technique

9.1.1. Use of Trend Charts

Visual comparison of the variations and trends in the bucket or injection temperatures as compared to the uncorrected zero depth values for the corresponding Bathythermograms is one of the best methods for determining the reliability of correcting the Bathythermograph sets by this independent measurement.

When sudden changes or discontinuities appear in the trend charts, three possibilities are evident:

(1) A change has occurred in the set of the BT (noted by a change in the zero-depth plot which is not followed by a corresponding change in the bucket temperatures).

(2) A change has occurred in the injection thermometer, due to error of reading, or failure of the instrument (noted by discontinuity in the bucket temperature plot not observed with the Bathythermograph zero depth values).

(3) A change has occurred in both curves, representing a decided change in ocean conditions.

The degree of "randomness" can be observed in both curves, which is a good indication as to the relative accuracies of both instruments. Where the randomness of the bucket temperatures is small compared to that of the zero depth value of the Bathythermograph, then this is good indication that individual, rather than average, correction factors be applied. If the converse is true, then average correction factors are better.

A notable exception to this rule occurs when the bucket or injection temperature shows no variation whatsoever over a period of time. This is not an indication of a good instrument, but rather it is an indication that no readings were made, and the value of the last reading taken was repeated over and over. Contrary to the rule of low randomness, this indicates a very unreliable bucket or injection thermometer reading, and the average values should be relied upon.

9.1.2. Comparison of Standard Deviations

When the average value is calculated for a series of zero depth values, and a corresponding average is obtained for the injection or bucket thermometer values, their standard deviations from this average can also be obtained.

With reliable instruments, both standard deviations should be approximately equal, representing for the most part the variations in the ocean. (See Section 4.3, Equation 3). If the two standard deviations are not similar, either one of two conditions is prevalent: (1) the one with the larger standard deviation has less accuracy and reliability; (2) the one with the smaller deviation represents a case of repeated readings rather than measured ones. The latter case can be quickly determined from the individual values.

9.1.3. Evaluation of Variability Data by the Coefficient of Correlation

The extent to which the data represent true ocean variability as opposed to the random errors of the two measuring instruments can be obtained through the coefficient of correlation. For any two independent measurements, the extent to which one measurement is dependent upon the other, i.e., Y is a function of X, is given by the correlation coefficient.

If the coefficient of correlation is high, then the variations of the readings of both instruments are a measure of variations in the ocean itself. If the coefficient of correlation is low, then the variations of both instruments are random variations and no conclusions about ocean variability should be attempted.

The coefficient of correlation may be derived mathematically as follows:

$$r = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - \overline{x}}{\sigma_x}\right)\left(\frac{y_i - \overline{y}}{\sigma_y}\right) \tag{1}$$

Where r = coefficient of correlation

N = number of readings

$\overline{x}$ = arithmetic average of the raw score, or $\frac{1}{N}\sum_{i=1}^{N} X_i$

x_i = each individual reading

$\overline{y}$ and y_i are defined as $\overline{x}$ and x_i (specifically applied, x_i and $\overline{x}$ are the individual and average bucket temperatures, while y_i and y are the corresponding individual and average zero depth values of the Bathythermogram.

σ_x = standard deviation of x_i

σ_y = standard deviation of y_i

The coefficient of correlation of two sets of variates, expressed in their standard deviation as units, is the arithmetic mean of the products of deviations of corresponding sets of values from their respective means.

Since σ_x and σ_y are constant:

$$r = \frac{1}{N}\frac{\Sigma(x_i - \overline{x})(y_i - \overline{y})}{\sigma_x\sigma_y} \tag{2}$$

From the coefficient of correlation, the extent to which the readings of both instruments expressed in standard deviations measure ocean variability can be obtained. This is derived as follows:

$$S_y = \sigma_y \ (1-r^2)^{\frac{1}{2}} \tag{3}$$

$$S_x = \sigma_x \ (1-r^2)^{\frac{1}{2}} \tag{4}$$

Where S_y = standard error of estimate of y

S_x = standard error of estimate of x

If the correlation is extremely high, the standard error of estimate corresponds to the random errors of the instrument:

From Section 4.3:

$$S_y = (\sigma_T)_{\text{INSTR.}} \tag{5}$$

Thus:

$$(\sigma_T)_{\text{TOTAL}} = \sqrt{\Sigma(\sigma_T)^2_{\text{OCEAN}} + \Sigma(\sigma_T)^2_{\text{INSTR.}}} \tag{6}$$

$$\sigma_y = \sqrt{(\sigma_T)^2_{\text{OCEAN}} + (\sigma_T)^2_{\text{INSTR.}}} \tag{7}$$

Combining Equations (3), (5) and (7):

$$\frac{(\sigma_T)^2_{\text{INSTR.}}}{1-r^2} = (\sigma_T)^2_{\text{OCEAN}} + (\sigma_T)^2_{\text{INSTR.}} \tag{8}$$

Which reduces to

$$\frac{(\sigma_T)_{\text{OCEAN}}}{(\sigma_T)_{\text{INSTR.}}} = \frac{r}{\sqrt{1-r^2}} \tag{9}$$

The coefficient of correlation does not indicate the relative reliability of the instruments (Bathythermograph and bucket or injection thermometer). The magnitude of the standard deviations must also be considered.

When the coefficient of correlation is high and the standard deviations are equal, the resulting standard errors of estimate are low, and both instruments are relaible to the accuracy of the standard error of estimate. The ocean variability can then be measured by the standard deviations.

When the coefficient of correlation is low and the standard deviations are also low, there may be negligible ocean variability, assuming the conditions of 9.1.2 are observed.

When the coefficient of correlation is low, and the standard deviations are high, one or both of the instruments has a high random error. If the magnitudes of the two standard deviations are dissimilar, probably the instrument with the higher standard deviation is the culprit. In any case, no reliability can be placed on the data representing ocean variability.

9.2. Use of Two Bathythermographs Simultaneously

The use of two Bathythermographs simultaneously rather than one Bathythermograph and bucket thermometer will give invaluable information in regard to ocean variability versus random error.

Employment of the coefficient of correlation as outlined above, but using the values recorded by the two Bathythermographs, (not only at the zero depth value but at many depths) will provide a measure as to the extent of ocean variability and random error of the instruments.

High correlation coefficients between the two Bathythermographs will indicate that the variations observed are really in the ocean. Low correlation coefficients will reveal that these variations are random errors of the instrument.

The two Bathythermographs should be on the same cable and as close together as possible. Also they should be reliable instruments, and matched, to the extent that the random errors should be about equal in magnitude.

9.3. Other Techniques to Correct Bathythermograph Sets

In lieu of employing an independent temperature measurement to correct the Bathythermograph to read absolute temperature values, other techniques present good possibilities. These are discussed in categories below.

9.3.1. Correction of Bathythermograms through Heat Content Studies

Theoretical studies can be undertaken assuming that no significant change in the heat content of the water will exist over this time of study. This condition is especially true where the ship which took the Bathythermograms was in a relatively fixed position during the time the Bathythermograms were taken. Any apparent large change in heat content represented by the temperature measurements of the Bathythermograph could therefore be considered to be produced by an error in the Bathythermogram values. Furthermore, this error can be considered a translation of the slide, or in other words a variation in the set of the Bathythermograph.

By integrating each Bathythermogram with respect to temperature an arbitrary heat content value can be established. This is in accordance with the following equations:

$$Q_{Z_2-Z_1} = \int_{Z_1}^{Z_2} A\,\bar{\rho}\,C_P(T_{Z_1}-T_{Z_2})dZ \qquad (1)$$

where Z_1 and Z_2 are the depths from which the integration takes place.
Where A, $\bar{\rho}$, C_P (area, average density, and specific heat) are constant, as would be the case in comparing Bathythermograph traces representing nearly constant conditions, the equation reduces to the following:

$$\frac{Q}{A\bar{\rho}C_P} = K = \int_0^Z (T_0 - T_{Z_2})dZ \qquad (2)$$

where the integration takes place from the surface to the bottom of the trace.
The Bathythermogram trace represents temperature as a function of depth,

i.e.:

$$T_Z = f(Z) \qquad (3)$$

Combining (2) and (3): $$K = \int_0^{Z_2} f(Z)\,dZ \qquad (4)$$

Thus solve for K for each Bathythermogram.

Without regard as to which Bathythermogram represents the true heat content of the ocean, each Bathythermogram in the series can be compared to some arbitrary reference heat content. Having established a quantity which must be added or subtracted from each individual Bathythermogram in order to make the heat content equal, this quantity can be re-translated into terms of a ΔT. This ΔT is the correction factor which should be applied to the Bathythermogram to cause the Bathythermogram to register the same heat content.

This technique cannot be applied to ocean conditions where considerable internal waves are present. Internal waves will represent an actual change in heat content of the ocean at that point from BT reading to BT reading. This technique would erroneously provide for a horizontal displacement of the Bathythermogram to overcome a vertical displacement in the water. In cases where internal waves are present, other techniques such as curve fitting techniques to be described below will have to be employed.

9.3.2. Curve Fitting Techniques

Thus far the processes for comparing Bathythermograph data have involved the use of their absolute grid values and various applied correction factors. A much more accurate picture of variation in the ocean can be obtained if the determinate errors of the instrument and the man-made determinate errors are first eliminated. This can be accomplished if the individual Bathythermograms are compared, not by their absolute grid values, but rather by superimposing one curve on top of another and noting the variations between the curves. This is a method for correcting the Bathythermograms; i.e., superimposing the non-varying portions of the curves upon each other.

This in actuality is correcting the temperatures at many depths rather than trying to correct the Bathythermograph by one single temperature measurement at the surface. The absolute value of the superimposed curve is still undetermined, but nevertheless the ocean variability can be shown by comparing the variations of these superimposed curves.

The assumption involved in curve fitting techniques are that the areas which are being investigated are relatively stable to begin with, and it is quite unlikely that the ocean will change in displacement throughout the entire exploration of the BT unit. It is considered then that the average deviation which is obtained by this type of comparison comes closer to approximating the true ocean variation than comparing BT's by their absolute values.

Two techniques are available for fitting these curves. The simplest and perhaps the most reliable is visual comparison. This is accomplished by superimposing transparent Bathythermograph slides of a given series until the curves are matched in their greater proportion. A grid can then be placed over top of these to determine the magnitude of the variations between the two curves. Scale differences must be considered.

If is is desired, a rigid mathematical approach can be applied to the curve fitting techniques. Several mathematical techniques have been suggested (refer to literature survey at the end of this report). It will require further study to determine the practicality and desirability of applying mathematical techniques in lieu of visual superimposition.

9.3.3. Correcting the Bathythermograms by the Permanent Thermocline

Where variations in the ocean are expected to be considerable, curve fitting techniques cannot be employed. However, there is indication that the bottom-most portion of the Bathythermograph will remain fairly stable even in conditions of high variability in the upper level. This bottom portion of the curve will be stable if it reaches the top of the permanent thermocline. This occurs only with 900 foot Bathythermographs.

It has been shown that the top of the permanent thermocline is fairly stable all year round, having variations not greater than present limitations of correcting Bathythermograph data. Where the top of the thermocline is reached by the bottom-most part of the trace, the trace can be superimposed. One is not depending upon an independent temperature measurement at this point, but depending upon the fact that this point does not vary in time, at least to any significant extent. This is a much better point to correct the Bathythermograph than the surface, which does vary considerably.

The additional information which is received and the ability to reach into a fairly stable portion of the ocean warrants the use exclusively of the 900 foot Bathythermographs. The present state of development of the 900 foot Bathythermograph is such that large failures in the bellows exist at this time. However, it is felt that emphasis should be placed upon extended use of the 900 foot Bathythermograph.

9.3.4. Use of Minimum Thermometer to Correct Bathythermographs

In cases where the bottom of the trace does not reach the top of the permanent thermocline and the variability of this part of the ocean is high, an independent temperature measurement would have to be made at the bottom of the trace. This is still an advantageous position to take an individual temperature measurement as opposed to the surface; because whatever the variability at this point, it is less than the top.

This suggests in lieu of the bucket or injection thermometer the use of an instrument which would measure the temperature at the maximum depth to which the Bathythermograph went. Such a minimum registering thermometer will have to have a good response characteristic and would have to be designed to indicate the temperature at that point, when brought out at the surface. The depth value would not have to be recorded since it would be fixed to the Bathythermograph.

While not much consideration has been given to the practicality of such an instrument, nevertherless in theory it would be highly advantageous over the present techniques of correcting Bathythermographs at the surface.

9.4. Establishment of Average Bathythermograms

In many studies it is desirable to establish a typical average Bathythermograph profile which is representative of the conditions over which the average was taken. The recording of temperatures at given specific depths from which an average temperature at each depth is then taken and from which an average Bathythermograph is drawn often leads to erroneous results. This is especially true where internal waves exist or where large variations in Bathythermograph sets exist. Such an average will round off any sharp corners in the Bathythermograph profile and distort the actual gradients which exist. This technique must be foregone in lieu of the more accurate curve fitting techniques as described above.

Proper curve fitting techniques can be used not only to determine the variations of the ocean, but also to obtain a typical average Bathythermograph. This type of

averaging technique will maintain the basic profile structure without distortion, and will provide a more accurate picture than the normal averaging of isothermal charts or isodepth charts. This technique can either be a visual one or a mathematical one.

9.5. Establishing Average Trends

There are many instances of study where long range trends are desired. These long range trends can be obscured by the individual variations such as standing waves, spurious data, etc., which are of short-term duration. In its place an average trend is desired which minimizes or eliminates these short-term variations.

The technique employed to establish an average trend is to establish a series of average Bathythermograms from which the average trends can be taken. The question arises as to the length of time over which an average should be made. Since for any average Bathythermogram which is desired the average or standard deviations can be obtained, the duration over which the Bathythermographs are averaged should be such that the deviations of the average Bathythermogram should not exceed the minimum differential which is desired in establishing the trend. If at any time the deviations of the average Bathythermogram are greater than the desired differential in trends, these trends have no mathematical significance, and should either be ignored or reworked with a smaller average Bathythermogram.

It should be noted that the average Bathythermogram which is made will produce erroneous or distorted results unless obtained as described in Section 9.3.

SECTION 10.0

RECOMMENDATIONS

Based on this study of the errors of the Bathythermograph, the following recommendations are made. These recommendations are broken down into the various categories below.

10.1. Bathythermograph Instrument

1. Eliminate the bending of the pen arm caused by excessive heating by the sun and the bellows table override.
2. Displace the uptrace from the downtrace of the BT for further clarity.
3. Place greater emphasis on the 900 foot Bathythermograph and correct its high incidence of bellows failure. Wherever possible, use the 900 foot Bathythermograph exclusively, in preference to the shallower ones.
4. Check the Bathythermograph frequently for loose parts during its use.
5. Re-evaluate the Bathythermograph's specifications in the light of the extensive experience which has been obtained in its use since the specifications were written.

10.2. Calibration

6. Use a pre-repair test on all Bathythermograms before recalibration.
7. Calibrate Bathythermographs quite frequently, at least every three months.
8. Keep a Bathythermograph log of repair history.
9. Obtain uniformity between testing stations.
10. Increase capacity of testing stations.
11. Test all Bathythermographs for the following things in addition to what is now being done:
    a. Hysteresis
    b. Response Rate
    c. Reproducibility
    d. Smoothness of Response

10.3. Operational Use of Bathythermograph

12. Use an adjustable speed winch.
13. Instruct personnel as to the importance of the data and the care required in taking it. This should be developed into an extensive training program.
14. Maintain complete notes on the conditions which prevail at the time each Bathythermograph cast is made, including every irregularity observed.

10.4. Correcting Bathythermograph Traces

15. Use better injection thermometers.
16. Use better bucket thermometers.
17. Use reliable, well insulated buckets.
18. Study the possibility of using independent check point located at a considerable depth of the ocean rather than at the surface.

10.5. Further Studies of the Errors of the Bathythermograph

10.5.1. Bathythermograph Sets

19. At present, average depth correction factors are used for an entire series of Bathythermograms. It is felt that a study of anchor stations representing a cross-sectional range from accurate data to poor data should be made in order to compare the advantages of applying depth correction factors to each card individually versus the present practice of applying an overall average correction. It is hoped that a formula can be evolved which will show when each practice would be most advantageous.

20. The bucket temperatures used to correct Bathythermograms are often subject to greater error than the Bathythermograms themselves. It is desired to study these variations between bucket and surface values of Bathythermograms through statistical analyses. It is hoped in this manner that factors can be found which will indicate whether to use correction factors or not. Other methods of investigating temperature correction factors would be curve fitting through superimposition and least square fit.

10.5.2. Variation in Bathythermograph Sets

21. A study of change or variation in set with each lowering should be further investigated, being easily accomplished through analysis of data from the anchor stations employed to accomplish Recommendations 19 and 20. An evaluation of the extent and amount of this variation should be forthcoming from such investigations.

22. Variation from fatigue and extended use of the Bathythermograph is best evaluated by the direct measure of the change which occurs in its calibration. This can be accomplished in the calibration procedures by measuring the calibration before the Bathythermograph is repaired. This can be compared to the last calibration.

23. Abnormal handling is indicated by a quite sudden change in the set. Sudden changes in set affect the averaging techniques employed in set corrections and should be studies with respect to their lack of recognition in computing average corrections. This should be studied in the anchor stations employed for Recommendations 19, 20, 21 and 22.

24. There are studies which show the depth set varies with depth. Further investigation is in order to determine the change as a function of depth. This is best accomplished by further experimental procedures involving comparisons to independent measuring instruments. Comparison of calibration slides periodically can also show the presence of a depth error.

25. Since pressure effects the bourdon tube, there may be a variation in the temperature set which is a function of depth. The study is best accomplished as outlined in Recommendation 24.

10.5.3. Calibration Errors

26. Calibration sets can occur unless duplicate tests are run, especially when new bellows are installed. Calibration sets are best evaluated experimentally through the calibration procedure.

27. A study is in order to determine the extent of variation present due to the assumption of linearity over the temperature scale and depth scale. At present,

equidistant spacing is employed for both temperature and depth. Comparison between the actual grid from a calibration tank and the approximated grid employed to make up the standard calibration would show these errors best.

10.5.4. Reproducibility

28. Reproducibility is best measured by the closeness with which the uptrace matches the downtrace, ocean variability being accounted for. A study of a series of Bathythermograms will reveal the extent of the following possible characteristics contributing to reproducibility.

(a) **Mechanical Hysteresis**

Mechanical hysteresis is represented by parallel displaced lines in a Bathythermogram study. Other effects of this mechanical lag might be observed.

(b) **Response to Initial Depths**

Response of the Bathythermograph to the first ten feet of water should be studied further experimentally. This is particularly important to understand because of its bearing upon the studies of keying the surface value of the Bathythermograph to a bucket temperature. It ties in with BT-bucket correlation analyses.

(c) **Rate of Response to Ocean Variations**

Response rates should be experimentally ascertained. This is important in relation to variability studies, internal wave studies, and will dictate operational procedures in proper rates of lowering, etc.

(d) **Response Hysteresis**

It is felt that a study of Bathythermograms can incorporate a study of all hysteresis effects. Response hysteresis should be able to be distinguished by the characteristic shape of the curves, and possibly some quantitative information can be produced from a study of the hysteresis curve shapes.

(e) **Mechanical Hesitation**

The wiggles on Bathythermograms can be due to mechanical hesitation through sticky bellows, pen play, etc. This must be experimentally evaluated through control tests.

10.5.5. Operational Errors

29. Studies have been made in order to evaluate personnel error. It is considered feasible to incorporate into the before-mentioned anchor station studies a personnel factor, this being accomplished by comparing anchor stations of various grades of accuracy, i.e., good, average, poor. Other studies along this line have been fairly quantitative in their results.

30. With regard to speed of raising and lowering the Bathythermograph, direct experimentation is necessary, along with the hysteresis analysis mentioned in Recommendation 28.

31. Bathythermogram reading errors can be established also on an experimental basis.

10.5.6. **Other Methods to Correct Bathythermograph's Temperature**

32. Other methods of keying Bathythermographs together are open to study and should be investigated. For such purposes a range of anchor stations should be studied: superior, typical, and even injection temperature stations.

33. The technique of lowering two Bathythermographs simultaneously and applying correlation studies to minimize instrument error should be investigated.

SECTION 11.0

GLOSSARY OF TERMS

The following is a partial list of terms employed in the oceanographic and mathematical fields. These terms are submitted in the hope that they will not only serve to clarify the terminology used in the report, but will also act as a basis for a more extensive and amended glossary in the field of Oceanography.

A

Absolute Value:	See Value, Absolute.
Accidental Error:	See Error, Accidental.
Accuracy:	The degree of concordance of a number representing the value of a quantity and the number representing the true value of the quantity; it may be expressed in either absolute or relative terms. This is a qualitative definition, since the true value of many quantities can never be known.
Advection:	Movement of water mass into or out of a fixed locality because of ocean currents, upwelling, etc.
Anchor Station:	Position occupied by a hydrographic vessel which is in a fixed locality. The more correct application of the term is made to vessels specifically at anchor, although it is sometimes applied to ships adrift.
Average Bathythermogram:	See Bathythermogram, Average.
Average Deviation:	See Deviation, Average.
Average Difference:	See Difference, Average.
Average Value:	See Value, Average.

B

Bathythermogram:	Photographic reproduction of a Bathythermograph slide which has the Bathythermograph grid superimposed for reading the temperature and depth values, the necessary temperature and depth correction having been applied in superimposing the grid.
Bathythermogram, Average:	A Bathythermogram calculated by employing average temperature values for a fixed locality over a period of time. Average Bathythermograms may be obtained by a number of averaging techniques, such as curve fitting, mathematical regression lines, least square, etc.
Bathythermograph:	Instrument which measures the change of temperature with the corresponding change in depth of the ocean. It employs a pressure bellows element to register depth changes and liquid filled temperature element to register change in temperature. The data are given in the form of a curve of temperature versus depth, or a smoked slide.

Bathythermograph Card: A Bathythermogram.

Bathythermograph Curve: Trace made on a Bathythermograph smoked slide by the pen arm. Represents change of temperature with change of depth.

Bathythermograph Data: Data in the form of temperature values, depth values, slope of temperature-depth trace, and points of inflection which are obtained from Bathythermograms.

Bathythermograph Grid: Graph lines, the abscissas of which represent line of constant depth, and the ordinates of which represent lines of constant temperature, photographed on a photo-sensitive glass slide and mounted in a viewer. Purpose of the grid is to translate directly the Bathythermograph curve into quantitative values of temperature and depth.

Bathythermograph Profile: See Profile, Bathythermograph.

Bathythermograph Slide: Smoked glass slide on which the Bathythermograph trace is drawn by the pen arm.

Bathythermograph Unit: A Bathythermograph; a Bathythermograph instrument.

Bathythermography: The art of taking, analyzing, and utilizing Bathythermographs.

Blotches: Marks left on BT slide by sporadic movement of the pen arm, usually caused by a sudden shock to the BT itself. Marks resemble jagged lines or ink spots.

BT: Abbreviation for Bathythermograph.

BTgm: Abbreviation for Bathythermogram.

Bucket Temperature: See Temperature, Bucket.

C

Characteristic Shape: The term refers to the BT trace, and specifies the general overall appearance of the curve. Since the BT trace often represents a typical ocean condition, this ocean condition is recognized by the "characteristic shape" of the Bathythermogram.
In formulating an average BTgm, it is most important to maintain the characteristic shape of the individual BTgms.

Component of Error: That individual error which stems from a distinct source, this error being one in a group of errors, each emanating from a distinct source, which together produce the overall error.

Consistency: Regularity with which the data seem to fit the particular conditions.

Correction Factor: The numerical value which is added to or subtracted from the location of the BT slide with respect to the BT grid to correct for the determinate errors or sets of the Bathythermograph.

DCS: Average difference between the 0 depth trace of the slide and the surface line (0 feet) of the reading grid. If the depth trace is above the zero foot line, the DCS is plus.

If the depth trace is below the zero foot line, the DCS is minus.
When the BTgm is photographed, this correction is applied, thus giving a correct BTgm.

DSP: Depth correction of the BTgm or photographic print. In case the error was not fully corrected in the making of the BTgm, there is a correction factor to be applied to the final print. The DSP is recorded in such a manner that the set correction to be applied is obtained by adding the DSP to the DCS. When no correction is necessary, the DSP will be equal in magnitude but opposite in sign to the DCS.

TCS: Average difference between the surface temperature as read from bucket or intake thermometer and the surface temperature as read from the slides. If the surface temperature is greater than the temperature of the slide, the TCS is plus. If it is less, the TCS is minus.

TSP: Temperature correction of the BTgm applied in the same way as described under DSP.

Correlation: The degree of relationship which may exist between two variables.

Correlation Coefficient: The correlation coefficient of the two sets of variates expressed in their respective standard deviations as units, is the arithmetic mean of the products of deviation of corresponding values from their respective means.

Cross Plotting: Process of replotting a set of data by interchanging the variables with the parameter. For instance, temperature versus time with depth as the parameter can be replotted as depth versus time with temperature as the parameter.

Curve Fitting: Process of relating two or more BTgms together by comparing how close the curves will match in characteristic shape. This process may be visual and qualitative, or may be precise and mathematical. The mathematical solutions also include the process of fitting a smooth curve through a set of discreet points. In the case of BTgms, the discreet points are replaced by a whole curve.

Cyclical Variations: See Variations, Cyclical.

D

DCS: See Correction Factor.

Dependent Error: See Error, Dependent.

Depth Displacement: See Displacement, Depth.

Depth Set: See Set.

Determinate Error: See Error, Determinate.

Deviation: Arithmetic difference between the average value of any one single value which contributed to the average value.

Deviation, Average: The Arithmetic mean of the deviations of a series of measurements of equal weight taken without regard to sign. The sum of the absolute values of deviations divided by the total number of deviations.

Deviation, Standard: The square root of the following quantity: the sum of the squares of the deviations of a series of measurements divided by the total number of deviations.

Discrepancy: The mathematical difference between two measurements of the same conditions, these measurements being taken simultaneously by two different measuring instruments.

Displacement: Translation of the origin of a set of coordinates; the difference, both in magnitude and direction, between the origins of two or more coordinate systems. Specifically, the displacement of a BTgm is the amount that the BT curve lies to the right or left of, up or down from a reference curve, or reference point. This displacement can be caused by sets in the instrument, can represent correction factors, comparisons between curves, etc.

Displacement, Temperature: Translation of the origin of a coordinate system of temperature versus depth, such displacement occurring in the direction of temperature.

Displacement, Depth: Translation of the origin of a coordinate system, temperature versus depth, such displacement occurring in the direction of depth.

Distortion: Change in the characteristic shape of the BT trace in any one portion not attributable to true ocean condition, but such change being caused by erroneous measurements, faulty instrument, or poor averaging technique.

Distribution, Gaussian or Normal: A measure of the occurrence of accidental errors in a series of measurements of the same degree of precision. The mathematical treatment is based on three axioms:

(1) Small errors are more frequent than large ones, and the probability of occurrence of an error is a function of its size.

(2) Positive and negative errors of the same size are about equal in number.

(3) Accidental errors of large magnitude do not occur.

Down Trace: See Trace, Down.

Drifting Station: See Anchor Station.

D.S.P: See Correction Factors.

E

Error: A class of deviations which describe the absolute or probable limits of reliability of a single measurement or a group of measurements. The term is too general for quantitative evaluation, since there are many kinds of errors. Generally the term error is used when in actuality the term indeterminate error should be used. Hence the more specific meaning is understood in the use of the more general term.

Error, Absolute: See Error, True.

Error, Accidental: Those deviations, inevitable in all measurements, which result from small unavoidable errors of observation due to more or less fortuitous variation in the sensitivity of our measuring instruments and the keenness of our senses of perception. Such errors are due to the combined effect of a large number of undetermined causes.

Error, Dependent: An error produced in a dependent variable by the error of the independent variable. Where Y is a function of X, an error in X will produce an error in Y. Referring to BTgms, where temperatures are a function of depth, an error in depth will produce a corresponding error in temperature.

Error, Determinate: An error that is discovered and allowed for in magnitude and sign in the form of a correction allowing for its effect.

Error, Independent: That portion of the error of a dependent variable which in itself is not a function of the error of the independent variable; these are accidental errors inherent in the measurement of that variable.

Error, Indeterminate: That error which cannot or is not properly allowed for in magnitude and sign. All errors that are not determinate errors.

Error, Instrument: Those errors which are specifically related to the measuring instrument. These comprise both determinate errors (sometimes called sets) and indeterminate errors (called instrument precision or reproducibility).

Error, Mean: See Deviation, Average.

Error, Mean Square: See Deviation, Standard.

Error Probable: An error of such magnitude that from the standpoint of probability the true error of the observation is just as likely to be greater as it is to be less than this magnitude.
More generally, it is a measure of the closeness with which the probable value approaches the true value.

Error, Reading: That error introduced into the measurements by the accuracy with which the observer can read the measured value of the instruments used to take the measurement.

Error, True: The difference between the observed or calculated value and the true value.

G

Gaussian Distribution: See Distribution, Gaussian or Normal.

Geological: Pertaining to the science which treats the history of the earth and its life, or the materials of the earth itself.
In Oceanography, *geological* pertains to the study of the ocean floor formations.

Gradient: Rate of change of one dependent variable with respect to the independent variable; slope; first derivative. As applied to BTgm, it is the slope of the curve.

Gradient, Negative:	Dependent variable decreases with increasing independent variable. As applied to the BTgm, it represents a decrease in temperature with increase in depth.
Gradient, Positive:	Dependent Variable increases with increasing independent variable. As applied to the BTgm, it represents an increase in temperature with increase in depth.
Gradient, Temperature:	Rate of change of temperature with change of depth of the ocean.
Grid:	See Bathythermograph Grid.
Gross Changes:	Changes in conditions of the ocean which are of an order of magnitude greater than the thermal microstructural changes which may occur.

H

Hysteresis:	As applied to Bathythermography only, hysteresis represents the lack of the uptrace to follow the downtrace, resulting in a typical hysteresis loop. Such loop resembles a new moon or parallel curves that converge at both ends.

I

Independent Error:	See Error, Independent.
Injection Temperature:	See Temperature, Injection.
Instrument Deviation:	See Deviation, Instrument.
Instrument Error:	See Error, Instrument.
Instrument Precision:	See Precision, Instrument.
Instrument Reproducibility:	See Reproducibility, Instrument.
Instrument Set:	See Set.
Interpolation:	Method of predicting the location of a point or points on a graph by assuming the data on either side of the interpolated region closely follow a smooth curve.
Isodepth Chart:	See Profile, Isodepth.
Isodepth Line:	Line connecting points of equal depth. Usually such a line represents temperature versus time or distance at a constant depth.
Isodepth Profile:	See Profile, Isodepth.
Isotherm:	Line connecting points of equal temperature. Usually such a line represents depth versus time or distance at constant temperature.
Isothermal Profile:	See Profile, Isothermal.

K

Keying Bathythermograms:	Process of relating the reference temperatures of a series of BTgms so as to compare the changes from BTgm to BTgm without being subject to the errors involved in establishing and maintaining these reference temperatures.

L

Lateral Variation: See Variation, Lateral.

M

Mass Movement: Displacement of water by advection, ocean currents, or internal waves.

Mean Square Error: See Error, Mean Square.

Microstructure, Thermal: Minute changes in the temperature of the ocean, in both lateral and vertical directions. These minute changes do not follow a predictable pattern, but are discontinuous and fluctuating.

N

Normal Distribution: See Distribution, Normal.

O

Occupation: (Refers to usage such as "occupation of Anchor Station.") Maintenance of a fixed position in the ocean by a hydrographic vessel.

Ocean Stability: See Stability, Ocean.

Ocean Variation: See Variation, Ocean.

Oceanography: Oceanography embraces all studies pertaining to the sea and integrates the knowledge gained in the marine sciences that deal with such subjects as the ocean boundaries and bottom topography, the physics and marine biology.

P

Parameters: A third variable in terms of which the two coordinates x and y can be expressed, rather than in terms of each other.

Plot, Simultaneous: Graph of two or more BTgms (single or average) on the same coordinate system. These BTgms are not superimposed as would be done by curve fitting techniques, but maintain their specific reference values as individually recorded.

Precision, Instrument: Measure of the ability of an instrument to reproduce a reading or set of readings. Equivalent to Reproducibility. This bears no relation to accuracy, since the instrument may precisely reproduce an erroneous value.

Pressure Sensing Element: See Sensing Element, Pressure.

Probable Error: See Error, Probable.

Probable Value: See Value, Probable.

Profile: Graph of temperature, depth, and time, using any two as variables with the remainder as a parameter. Also called charts, and plots.

Profile, Bathythermograph: Plot of temperature versus depth, with a time parameter. Normally called a bathythermograph slide, if uncorrected, or a BTgm if corrected. Also called temperature profile.

Profile, Isodepth: Plot of temperature versus time with depth as the parameter. Also called isodepth charts, isodepth profiles; sometimes called isobaric profiles.

Profile, Isothermal: Plot of depth versus time with temperature as the parameter. Also called isothermal charts and plots.

Profile, Temperature: Usually refers to BTgms. Incorrectly refers to isothermal profile.

R

Readings: Discreet values or sets of values as read from the BTgms.

Reading, Average: Arithmetic mean of several values as read from BTgms.

Readings, Zero Depth: Temperature values as read from the BTgms corresponding to the surface of the ocean or abscissa coordinate labeled zero feet in depth.

Reading Error: See Error, Reading.

Regression Line: A straight line plotted among a scatter diagram of points (plotted to determine the extent of correlation between two variables) in such a way as to make the sum of the squares of the vertical distances from the points to the line a minimum.

Reproducibility: A measure of the closeness with which a measuring instrument will repeat its response to the same set of conditions. A measure of the closeness with which a series of repeated values resemble each other. See also Precision.

Residual: The difference between the most probable value and any individual measurement of the series.

S

Salinity: The total amount of solid matter in grams contained in one kilogram of sea water when all of the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized.

Sensing Element: Physical equipment which responds by change in some one of its characteristics to temperature, depth, or salinity.

Sensing Element, Pressure: Evacuated spring loaded compression bellows. Change of depth compresses or expands the bellows, changing the position of the BT slide.

Sensing Element, Temperature: Copper tubing filled with liquid and connected to a Bourdon tube. Change of temperature causes the liquid in the copper tube to expand or contract, transmitting the developed pressure to the Bourdon tube.

Set: Mathematical Value, both with magnitude and sign, which describes the amount by which the measured temperatures or depths depart from the true, or most probable, or calibrated value.

Set Variation: See Variation in Set.

Simultaneous Plot: See Plot, Simultaneous.

Slope: See Gradient.

Stability, Ocean: Mathematical term describing the extent to which water is in buoyant equilibrium at any point in the ocean. Refers to Dynamic stability.

Standard Deviation: See Deviation, Standard.

Superimposition: Act of placing the trace from one BT over the trace of another BT so as to coincide in all points possible by translating, but not rotating, the traces the necessary amount.

T

TCS: See Correction Factor.

Temperature, Bucket: Value of surface temperature of the ocean as read from a regular measuring thermometer which is placed in a bucket sample of surface water scooped up at the desired point of measurement by a specially designed bucket.

Temperature Displacement: See Displacement, Temperature

Temperature Gradient: See Gradient, Temperature.

Temperature, Injection: Surface temperature of the ocean as read from the injection thermometer which is located aboard ship at the point of cold water intake. The location of the intake is not actually at the surface, but may be a considerable distance below the water level.

Temperature Profile: See Profile, Temperature.

Temperature Sensing Element: See Sensing Element, Temperature.

Temperature Set: See Set.

Thermal Microstructure: See Microstructure, Thermal.

Thermocline: In its strictest sense, a transition layer of water at mid depths between the top surface layer which is isothermal and mixed, and a very deep mass of much colder water in which the temperature decreases very slightly and uniformly with depth.
The term, more generally applied, refers to any layer in which the temperature decreases markedly with depth.

Trace: Impression on the smoked BT slide etched by the temperature pen arm which represents a graph of temperature versus depth.

Trace, Down: Trace made during the descent of the BT.

Trace, Up: Trace made during the ascent of the BT.

Trend Chart: Plot of temperature or depth (single or average value) versus time, primarily used to indicate the trends or changes in these conditions with time.

True Error: See Error, True.

True Value: See Value, True.

TSP: See Correction, Factor.

U

Uncorrected Value: See Value, Uncorrected.

Uptrace: See Trace, Up.

V

Value, Absolute: *Math Def.:* Value without regard as to sign. *General:* True value; correct value to the limits of high accuracy when the true value is impossible to determine.

Value, Actual: Representative of the thermal state in reference coordinates corresponding to the standard temperature scale as opposed to arbitrary reference coordinates.

Value, Average: Arithmetic means of a series of measurements, all of which have equal weight or are properly weighed and handled accordingly.

Value, Probable: Average value which must closely resemble the true value. It can be stated that the Probable Value is the value which does not exceed the true value by the Probable Error.

Value, Reference: Magnitude as related to a particular reference origin. When standard origins are used, the reference and actual value are identical.

Value, True: Value without error. Value by definition or standard.

Value, Uncorrected: Values of BTgms as read from a glass slide with grid placed in last calibrated position without application of set correction factors.

Value, Zero Depth: See Reading, Zero Depth.

Variance: Measure of the change with time or direction of an average or standard deviation.

Variations: Small random changes in measurements due either to true changes in the ocean parameters or in the measuring instruments themselves.

Variation, Cyclical: Harmonic variation of temperature or displacement due to internal waves.

Variation, Lateral: Change in conditions in a horizontal traverse.

Variation in Set: Change in magnitude of set which cannot be accounted or allowed for. Indeterminate portion of the determinate error of set.

Variation, Ocean: See Variability, Ocean.

Variability, Ocean: Indeterminate variations or changes in the ocean with time or direction which cannot be accounted for in magnitude and sign.

Z

Zero Depth Value: See Reading, Zero Depth.

Zero Depth Reading: See Reading, Zero Depth.

SECTION 12.0

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(1) Construction of BT
(2) Operation of BT
(3) Maintenance of BT
(4) Improvements in design of BT
(5) Accuracy of BT
(6) Comparison of BT with other instruments
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